Contents

1 Introduction ...................................................... 1
  1.1 Need for Control Performance Management (CPM) ........ 2
    1.1.1 Objectives and Importance of Control Assets .......... 3
    1.1.2 State of Industrial Process Control Performance ...... 6
    1.1.3 Root Causes of Control Performance Problems ....... 8
  1.2 Principle and Tasks of Control Performance Management .. 11
    1.2.1 Control Performance Indices ........................ 12
    1.2.2 Basic Procedure for Control Performance Management .. 14
    1.2.3 Controller Performance Assessment Benchmarks ....... 16
    1.2.4 Challenges of Performance Monitoring Applications ... 17
  1.3 Key Dates of the Development of CPM Technology and Literature Survey .................................. 18
  1.4 Outline of the Book ........................................... 22

Part I Evaluation of the Level of Control Performance

2 Assessment Based on Minimum-Variance Principles ............ 29
  2.1 System Descriptions and Basics ............................ 29
    2.1.1 Note on Input–Output Models .......................... 31
  2.2 Minimum-Variance Control (MVC) ........................... 32
  2.3 Auto-Correlation Test for Minimum Variance ............... 36
  2.4 Minimum-Variance Index/Harris Index ...................... 38
    2.4.1 Estimation from Time-Series Analysis .................. 39
    2.4.2 Estimation Algorithms ............................... 42
  2.5 Assessment of Feedback/Feedforward Controls ............. 49
  2.6 Assessment of Set-Point Tracking and Cascade Control .... 54
    2.6.1 Performance Assessment of Cascade Control Systems ... 54
    2.6.2 Assessment of Different Tuning Strategies ............ 60
  2.7 Summary and Conclusions .................................... 62

3 User-Specified Benchmarking .................................... 65
  3.1 General Setting ............................................... 65
### Contents

3.2 IMC-Achievable Performance Assessment ........................................... 66
  3.2.1 IMC Design ........................................................................ 67
  3.2.2 IMC Benchmark ................................................................... 70
3.3 Extended Horizon Approach ................................................................. 72
3.4 Performance Index Based on Desired Pole Locations .......................... 75
3.5 Historical or Reference Benchmarks .................................................... 76
3.6 Reference-Model/Relative Performance Index .................................... 76
  3.6.1 Selection of the Reference Model ........................................... 77
  3.6.2 Disturbance Estimation ......................................................... 77
  3.6.3 Selection of Critical Index Value ........................................... 78
  3.6.4 Index Properties .................................................................. 78
3.7 Summary and Conclusions ................................................................. 78

4 Advanced Control Performance Assessment ......................................... 81
  4.1 Generalised Minimum-Variance Control (GMVC) Benchmarking ........ 81
    4.1.1 GMVC Control .................................................................. 82
    4.1.2 Selection of Weightings ....................................................... 83
    4.1.3 GMVC with Static Weightings ............................................ 84
    4.1.4 Assessment Index and Procedure ........................................ 85
  4.2 Linear-Quadratic Gaussian (LQG) Benchmarking .............................. 86
    4.2.1 Classical LQG Framework .................................................. 89
    4.2.2 Polynomial Domain Approach ......................................... 89
    4.2.3 LQG Framework as Special Case of MPC ........................... 90
    4.2.4 Subspace-Based LQG Design ........................................... 90
    4.2.5 Generation of the LQG Performance Limit Curve ................. 91
    4.2.6 LQG Assessment Using Routine Operating Data ................. 92
  4.3 Model Predictive Control (MPC) Assessment .................................... 96
    4.3.1 Basic Principle and Properties ........................................... 97
    4.3.2 Constrained Minimum-Variance Control ........................... 101
    4.3.3 Design-Case MPC Benchmarking ..................................... 101
    4.3.4 Infinite-Horizon Model Predictive Control ......................... 102
    4.3.5 Assessing the Effect of Constraints ................................... 110
    4.3.6 Economic Performance Assessment of MPC ....................... 110
  4.4 Summary and Conclusions ............................................................ 117

5 Deterministic Controller Assessment ..................................................... 121
  5.1 Performance Metrics ................................................................. 121
  5.2 Controller Assessment Based on Set-Point Response Data .................. 123
    5.2.1 Normalised Criteria ......................................................... 123
    5.2.2 Assessment Methodology .................................................. 124
    5.2.3 Determination of Time Delay from Step Response ............... 126
    5.2.4 Application Examples ...................................................... 129
  5.3 Idle Index for Detecting Sluggish Control ....................................... 131
    5.3.1 Characterisation of Sluggish Control .................................. 132
    5.3.2 Idle Index ....................................................................... 133
Part II Detection and Diagnosis of Control Performance Problems

8 Statistical Process Control ........................................... 209
8.1 Univariate Statistical Process Control .......................... 209
8.2 Multivariate Statistical Process Control ...................... 212
8.2.1 Principal Component Analysis ................................. 212
8.2.2 Partial Least Squares ........................................... 214
8.2.3 Advanced Methods for Multivariate Statistical Process
     Control ................................................................. 215
8.3 Use for Control Performance Assessment ...................... 216
8.4 Summary and Conclusions ......................................... 217

9 Detection of Oscillating Control Loops ............................ 219
9.1 Root Causes of Poor Performance ................................. 219
9.2 Characterisation and Sources of Oscillations in Control Loops . 221
9.3 Detection of Peaks in the Power Spectrum ..................... 222
9.4 Regularity of “Large Enough” Integral of Absolute Error (IAE) 224
     9.4.1 Load-Disturbance Detection ................................. 224
     9.4.2 Basic Approach .............................................. 225
     9.4.3 Detection Procedure ......................................... 226
     9.4.4 Method Enhancement for Real-Time Oscillation Detection 226
9.5 Regularity of Upper and Lower Integral of Absolute Errors and
     Zero Crossings ...................................................... 228
     9.5.1 Basic Methodology ............................................ 228
     9.5.2 Practical Conditions and Parameter Selection ........... 229
9.6 Decay Ratio Approach of the Auto-covariance Function ........ 230
     9.6.1 Methodology .................................................. 230
     9.6.2 Practical Conditions and Parameter Selection ........... 232
9.7 Regularity of Zero Crossings of the Auto-covariance Function 233
9.8 Pitfalls of Multiple Oscillations—Need for Band-Pass Filtering 234
9.9 Detection of Intermittent Oscillations ........................... 237
9.10 Summary and Conclusions ......................................... 237

10 Detection of Loop Nonlinearities .................................. 239
10.1 Methods Review ................................................... 240
10.2 Bicoherence Technique ............................................ 241
     10.2.1 Non-Gaussianity Index ...................................... 242
     10.2.2 Nonlinearity Index .......................................... 243
     10.2.3 Procedure and Practical Conditions ...................... 244
     10.2.4 Modified Indices ............................................ 246
10.3 Surrogate Data Analysis .......................................... 248
     10.3.1 Generation of Surrogate Data ............................. 248
     10.3.2 Discriminating Statistics—Nonlinear Predictability
            Index ............................................................. 250
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.3.3</td>
<td>Nonlinearity Detection Procedure</td>
<td>251</td>
</tr>
<tr>
<td>10.3.4</td>
<td>Spurious Nonlinearity—Pitfalls in the Surrogate Data</td>
<td>252</td>
</tr>
<tr>
<td>10.3.5</td>
<td>Default Parameter Values and Practical Issues</td>
<td>255</td>
</tr>
<tr>
<td>10.4</td>
<td>Detection of Saturated Actuators</td>
<td>256</td>
</tr>
<tr>
<td>10.4.1</td>
<td>Saturation Test Based on Statistical Distribution</td>
<td>257</td>
</tr>
<tr>
<td>10.4.2</td>
<td>Saturation Index for Valve Monitoring</td>
<td>258</td>
</tr>
<tr>
<td>10.5</td>
<td>Comparative Studies</td>
<td>258</td>
</tr>
<tr>
<td>10.5.1</td>
<td>Unit-Wide Oscillation Caused by a Sensor Fault</td>
<td>259</td>
</tr>
<tr>
<td>10.5.2</td>
<td>Plant-Wide Oscillation Caused by a Valve Fault</td>
<td>261</td>
</tr>
<tr>
<td>10.6</td>
<td>Summary and Conclusions</td>
<td>263</td>
</tr>
<tr>
<td>11</td>
<td>Diagnosis of Stiction-Related Actuator Problems</td>
<td>265</td>
</tr>
<tr>
<td>11.1</td>
<td>Typical Valve-Controlled Loop</td>
<td>266</td>
</tr>
<tr>
<td>11.2</td>
<td>Effects Relating to Valve Nonlinearity</td>
<td>268</td>
</tr>
<tr>
<td>11.3</td>
<td>Stiction Analysis</td>
<td>269</td>
</tr>
<tr>
<td>11.3.1</td>
<td>Effect of Stiction in Control Loops</td>
<td>269</td>
</tr>
<tr>
<td>11.3.2</td>
<td>Physically Based Stiction Modelling</td>
<td>271</td>
</tr>
<tr>
<td>11.3.3</td>
<td>Data-Driven Stiction Modelling</td>
<td>272</td>
</tr>
<tr>
<td>11.3.4</td>
<td>Typical Trends of Variables and Input–Output Shape Analysis</td>
<td>274</td>
</tr>
<tr>
<td>11.4</td>
<td>Stiction Diagnosis Based on Shape Analysis of MV–OP Plots</td>
<td>277</td>
</tr>
<tr>
<td>11.4.1</td>
<td>Stuck Indices</td>
<td>278</td>
</tr>
<tr>
<td>11.5</td>
<td>Cross-Correlation-Based Stiction Detection</td>
<td>281</td>
</tr>
<tr>
<td>11.6</td>
<td>Diagnosis Based on Curve Fitting</td>
<td>284</td>
</tr>
<tr>
<td>11.6.1</td>
<td>Sinusoidal Fitting</td>
<td>285</td>
</tr>
<tr>
<td>11.6.2</td>
<td>Triangular Fitting</td>
<td>286</td>
</tr>
<tr>
<td>11.6.3</td>
<td>Stiction Index and Detection Procedure</td>
<td>286</td>
</tr>
<tr>
<td>11.6.4</td>
<td>Similar Techniques</td>
<td>288</td>
</tr>
<tr>
<td>11.7</td>
<td>Nonlinearity Detection and PV–OP Pattern Analysis</td>
<td>289</td>
</tr>
<tr>
<td>11.7.1</td>
<td>Stiction Detection and Estimation Procedure</td>
<td>289</td>
</tr>
<tr>
<td>11.7.2</td>
<td>Practical Issues</td>
<td>292</td>
</tr>
<tr>
<td>11.8</td>
<td>Tests to Confirm Stiction</td>
<td>294</td>
</tr>
<tr>
<td>11.8.1</td>
<td>Controller Gain Change Test</td>
<td>295</td>
</tr>
<tr>
<td>11.8.2</td>
<td>Valve Travel or Bump Test</td>
<td>296</td>
</tr>
<tr>
<td>11.9</td>
<td>Stiction Diagnosis Procedure</td>
<td>297</td>
</tr>
<tr>
<td>11.10</td>
<td>Summary and Conclusions</td>
<td>299</td>
</tr>
<tr>
<td>12</td>
<td>Complete Oscillation Diagnosis Based on Hammerstein Modelling</td>
<td>301</td>
</tr>
<tr>
<td>12.1</td>
<td>Features of the Proposed Framework</td>
<td>302</td>
</tr>
<tr>
<td>12.2</td>
<td>Identification Model Structure</td>
<td>303</td>
</tr>
<tr>
<td>12.3</td>
<td>Identification Algorithm</td>
<td>305</td>
</tr>
<tr>
<td>12.3.1</td>
<td>Linear Model Estimation</td>
<td>305</td>
</tr>
<tr>
<td>12.3.2</td>
<td>Nonlinear Model Estimation</td>
<td>308</td>
</tr>
<tr>
<td>12.4</td>
<td>Key Issues</td>
<td>311</td>
</tr>
</tbody>
</table>
12.4.2 Determination of Initial Parameters and Incorporation of Constraints ........................................... 312
12.5 Application and Results ........................................... 313
12.5.1 Simulation Studies ........................................... 313
12.5.2 Industrial Case Studies ........................................... 314
12.6 Detection of Multiple Loop Faults ........................................... 320
12.6.1 Simulation Examples ........................................... 323
12.6.2 Industrial Examples ........................................... 324
12.7 Summary and Conclusions ........................................... 329

Part III Performance Improvement

13 Performance Monitoring and Improvement Strategies .......... 333
13.1 Performance Improvement Measures ........................................... 333
13.2 Loop Monitoring Paradigms ........................................... 335
  13.2.1 Bottom-Up and Top-Down Approaches ........................................... 335
  13.2.2 Loop Prioritisation and Ranking ........................................... 337
  13.2.3 Relationship to Economical Benefits ........................................... 337
13.3 Comprehensive Procedure for Performance Monitoring ........................................... 338
13.4 Summary and Conclusions ........................................... 341

14 Controller Auto-Tuning Based on Control Performance Monitoring . 343
14.1 Basic Concepts of Controller Auto-Tuning and Adaptation ........................................... 345
14.2 Overview and Classification of CPM-Based Tuning Methods ........................................... 346
14.3 Optimisation-Based Assessment and Tuning ........................................... 347
  14.3.1 Methods Based on Complete Knowledge of System Model ........................................... 347
  14.3.2 Techniques Based on Routine and Set-Point Response Data ........................................... 356
14.4 Iterative Controller Assessment and Tuning ........................................... 362
  14.4.1 Techniques Based on Load Disturbance Changes ........................................... 362
  14.4.2 Methods Based on Routine Data and Impulse Response Assessment ........................................... 366
14.5 Strategies for Variation of Controller Parameters ........................................... 380
  14.5.1 Variation of Proportional Gain Alone and Fine Tuning of Integral Time ........................................... 380
  14.5.2 Simultaneous Variation ........................................... 381
  14.5.3 Successive Variation ........................................... 381
  14.5.4 Constraints and Loop Stability ........................................... 382
14.6 Comparative Studies ........................................... 383
14.7 Summary and Conclusions ........................................... 385

Part IV Applications and Tools

15 Industrial CPM Technology and Applications .......... 389
15.1 Demands on Performance Monitoring Algorithms ........................................... 389
15.2 Review of Control Performance Monitoring Applications ........................................... 391
  15.2.1 Analysis of Fields of Application ........................................... 393
15.2.2 Analysis of Type of Implemented Methods ........ 393
15.3 Review of Control Performance Monitoring Systems .... 393
  15.3.1 CPM Tools and Prototypes .......................... 393
  15.3.2 Commercial Products ............................... 394
15.4 Summary and Conclusions .............................. 396
15.5 Summary of Industrial Case Studies ..................... 397
16 Performance Monitoring of Metal Processing Control Systems .... 403
  16.1 Introduction to the Metal Processing Technology ....... 404
     16.1.1 Steel Processing Route and Control Objectives ...... 404
     16.1.2 Control Objectives .................................. 406
     16.1.3 Mill Automation ..................................... 409
     16.1.4 Overview of Metal Processing Control Systems ...... 411
     16.1.5 Technological Control Systems ....................... 414
  16.2 Practical Aspects of Performance Assessment in Metal Processing 415
     16.2.1 Online vs. Batch-Wise Evaluation .................... 415
     16.2.2 Oscillation Diagnosis ................................ 416
     16.2.3 Time-Based vs. Length-Based Assessment ............. 417
     16.2.4 User-Specified Indices .............................. 418
  16.3 Industrial Cases Studies and Developed Monitoring Tools ...... 418
     16.3.1 Gauge Control in Cold Tandem Mills ................ 419
     16.3.2 Flatness Control in Cold Tandem Mills ............... 424
     16.3.3 Temperature Control in Annealing Lines .......... 427
  16.4 Summary and Conclusions ................................ 439

Appendix A Basic Signal Processing and Statistics ............ 441
  A.1 Ergodicity ................................................. 441
  A.2 Expectation and Variance .................................. 441
  A.3 Correlation and Covariance ............................... 442
  A.4 Discrete Fourier Transform ............................... 443
  A.5 Power Spectrum and Coherence Function .................... 444

Appendix B Higher-Order Statistics ............................ 447
  B.1 Moments and Cumulants ................................. 447
  B.2 Polyspectra and Coherence Functions .................... 449
  B.3 Estimating the Bispectrum from Data .................... 451
  B.4 Skewness and Squared Bicoherence Functions .............. 452

Appendix C Control Loops from Different Industries .......... 457

References ................................................. 461

Index ...................................................... 481
Control Performance Management in Industrial Automation Assessment, Diagnosis and Improvement of Control Loop Performance
Jelali, M.
2013, XXVII, 480 p., Hardcover